Low Ghz loss in sputtered epitaxial Fe

C. Scheck, L. Cheng, W.E. Bailey
*Materials Science and Engineering Program, Dept. of Applied Physics and Applied Mathematics, Columbia University, 500 W 120th St, New York, NY 10027**

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We show that sputtered, pure epitaxial iron films can have high-frequency loss as low as, or lower than, any known metallic ferromagnetic heterostructure. Minimum 34 Ghz ferromagnetic resonance (FMR) linewidths of 41 ± 2 Oe are demonstrated, some ∼ 5-10 % lower than the previous minimum reported for molecular beam epitaxially (MBE) deposited Fe. Intrinsic and extrinsic damping have been separated over 0-40 Ghz, giving a lower bound for intrinsic LL(G) relaxation rates of λ or $G = 85 \pm 5$ MHz ($\alpha = 0.0027 \pm 0.0001$) and extrinsic $\eta \sim 50$ Mhz. Swept frequency measurements indicate the potential for integrated frequency domain devices with $Q > 100$ at 30-40 Ghz.

I. INTRODUCTION

Low damping α, or relaxation rates λ, are essential for high frequency applications of magnetic heterostructures. Nanoscale spin electronic sensors operating above 1 Ghz have signal-to-noise ratios (SNR) which depend inversely on the damping constant α and are independent of spin transport parameters.[1] Integrated magnetic frequency domain devices have frequency linewidths ($\Delta\omega/2\pi$) limited fundamentally by the Landau-Lifshitz-(Gilbert) relaxation rate $\lambda(= G) = \alpha\gamma M_s$,[2] where γ is the gyromagnetic ratio. It is timely to determine how low relaxation rates can be made in a ferromagnetic thin film, particularly using widely accessible deposition techniques such as sputtering.

Relaxation processes expressed phenomenologically in α[3] can be divided into extrinsic and intrinsic types. Extrinsic damping results from microstructure; intrinsic damping results from spin-orbit coupling.[4] The two effects can be separated through variable-frequency ferromagnetic resonance measurements (FMR), through $\Delta H_{pp} = \Delta H_0 + (2/\sqrt{3})\alpha/\gamma$.[5] α in this context expresses intrinsic processes, and ΔH_{pp} expresses inhomogeneous broadening due to e.g. line defects.[6]

The lowest overall linewidths have been seen in the ultrathin molecular beam epitaxially (MBE) deposited Fe films of Prinz, with a 35 Ghz $\Delta H_{pp} = 45$ Oe (1.29 Oe/Ghz) seen in ultrathin Fe(100) deposited on ZnSe(100) epilayers.[7] Intrinsic and extrinsic losses were not separated in the prior work, carried out at a single frequency. Fe also possesses the lowest known *intrinsic* damping constant of any metallic ferromagnet, with a range of λ quoted as $\lambda = 70$-140 Mhz ($\alpha = 0.002$-0.004) in FMR measurement to 40 Ghz.[8] Variable frequency FMR estimates of α over this range, through $\partial\Delta H/\partial\Delta\omega$, have typically uncovered values of 100 Mhz $\leq \lambda \leq 140$ Mhz in high-quality MBE[6, 9] or sputtered films.[10]

In this work, we report UHV sputtered epitaxial pure Fe(100)(15nm)/Ti(2nm) films on MgO(100) which show FMR linewidths of $\Delta H_{pp} = 41 \pm 2$ Oe at 34 Ghz (1.20 Oe/Ghz), some 5-10% lower than the narrowest linewidths seen to date in MBE deposited films. Variable frequency 0-40 Ghz FMR indentifies $\lambda = 85 \pm 5$ Mhz ($\alpha = 0.0027 \pm 0.0001$) and $\Delta H_0 \sim 6 \pm 2$ Oe for these thin films; a role of eddy current damping is identified in α of thicker Fe films. Swept-frequency measurements demonstrate the potential for field-tunable ∼ 35 Ghz filters with $Q > 100$, an order of magnitude better than achieved previously in Fe.

II. EXPERIMENTAL

Fe (8-75 nm) thin films were deposited on polished MgO(001) substrates using dc magnetron UHV sputtering at a base pressure of 3.0×10^{-9} Torr. Pressures immediately prior to deposition after sample introduction were typically 1.0×10^{-8} Torr. Substrates were held at 200 °C during sputter deposition, at 4×10^{-3} Torr *in-situ* getter-purified Ar, 300 W power for 2 inch targets, and 10 cm target-substrate spacing. Growth rates of ∼6 Å/s were measured by a quartz crystal microbalance and *ex-situ* profilometry. Films were capped with 2 nm sputtered Ti to protect the surface from oxidation. Rocking curve half widths measured for 50 nm films were very low, only 0.5 °, and roughly independent of deposition temperature over the range 200-300 °C. Results for ion beam sputtered $Ni_{81}Fe_{19}$(48 nm) are plotted for comparison; see Ref. [11] for deposition conditions.

Broadband FMR measurements were carried out using microwave frequencies in the range 4-40 Ghz generated by a synthesized sweep generator operating in cw mode. Microwaves were applied to the samples through a coplanar waveguide (CPW) for the range 4-18 Ghz[3] and a shorted K-band rectangular waveguide for higher frequencies, with diode detector in transmission and reflection, respectively. Derivative spectra $\Delta\chi''/\Delta H$ were recorded using ac field modulation ($< \pm 2$ G) and lock-in detection.[12] Swept-field and swept-frequency measurements were both carried out, at room temperature.

*URL: http://magnet.ap.columbia.edu

III. RESULTS

A representative FMR spectrum for thin (8 or 15 nm) Fe films at 34 Ghz is shown in Fig. 1. The film is measured with H applied along the <110> hard axis, along MgO<100>. The derivative spectrum is shown to be symmetric, with Lorenzian fit indicated, and peak-to-peak linewidth measured of $\Delta H_{pp} = 41 \pm 2$ Oe.

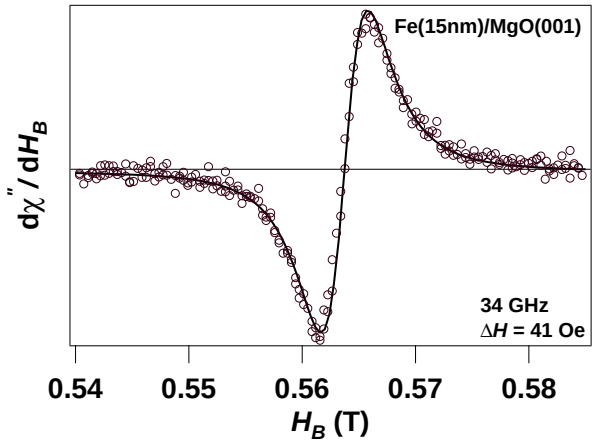

FIG. 1: 34 Ghz FMR spectrum, with Lorenzian fit, for epitaxially sputtered MgO(001)/Fe(15 nm)/Ti(2 nm). See text for details.

Peak-to-peak FMR linewidths ΔH_{pp} versus frequency $\omega/2\pi$ were plotted for all samples (Fig. 2) to determine the Landau-Lifshitz-Gilbert (LLG) damping constant α and the inhomogeneous broadening ΔH_0. From the slope $\partial\Delta H/\partial\Delta\omega$, we find a minimum $\alpha = 0.0027 \pm 0.0001$ for thin Fe (<15 nm). $\alpha = 0.0075$ is measured for $Ni_{81}Fe_{19}$(48nm), consistent with the lower bound of typical values and characteristic of high quality films. Relaxation rates λ are converted from α measurements using $g_{eff} = 2.09$[8] and $4\pi M_s^{Ni_{81}Fe_{19}} = 10.6$ kG, $4\pi M_s^{Fe} = 21.6$ kG, and plotted for comparison. λ reaches a minimum of 85 ± 5 Mhz for epitaxial Fe and 120 ± 10 Mhz for $Ni_{81}Fe_{19}$. Inhomogeneous broadening is negligible for $Ni_{81}Fe_{19}$, with $\Delta H_0 = 2 \pm 2$ Oe, and reaches a minimum of $\Delta H_0 = 6 \pm 2$ Oe for 15 nm Fe.

An increasing trend in α with thickness can be seen for Fe films thicker than 15 nm. We have compared the increase in λ with a standard theory of eddy current damping,[13] which predicts a quadratic increase in Gilbert-type (proportional to ω) linewidth with film thickness t:

$$\lambda_{\rm eddy} = \frac{\sigma}{12}(4\pi\gamma M_s)^2\left(\frac{t}{c}\right)^2 \qquad (1)$$

where σ is the conductivity (hz for cgs units) and c the speed of light in vacuum. σ values used for Fe and $Ni_{81}Fe_{19}$ were respectively 9.11×10^{16} hz (ρ = 10 $\mu\Omega$.cm from four-point-probe measurement) and 4.5×10^{16} hz (ρ = 20 $\mu\Omega$.cm). Order of magnitude agreement is found with the increase in λ for Fe films to 75 nm; the $Ni_{81}Fe_{19}$ data are plotted with thickness scale compressed by the ratio of the prefactors for the two materials (~ 8), indicating an expected delayed onset of eddy-current damping (> 200 nm) for $Ni_{81}Fe_{19}$. A thickness-dependent increase of the inhomogeneous term ΔH_0 from 6 to 30 Oe with increasing Fe thickness may originate in a higher concentration of strain-relaxing dislocations for thicker films.[6]

The advantage of swept-ω FMR measurement for extracting total relaxation rates η has been pointed out by Patton.[2] η can be measured independent of geometry

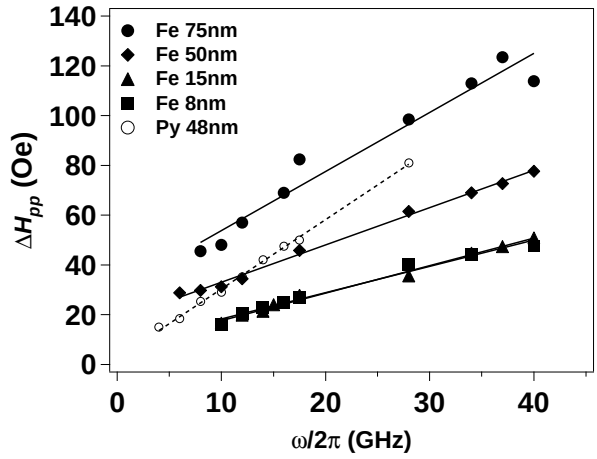

FIG. 2: Frequency dependent peak-to-peak FMR linewidths ΔH_{pp} for epitaxially sputtered MgO(100)/Fe(t), 8 nm < t < 75 nm, with linear fits to extract α. Data from polycrystalline $SiO_2/Ni_{81}Fe_{19}$(48 nm) are plotted for comparison.

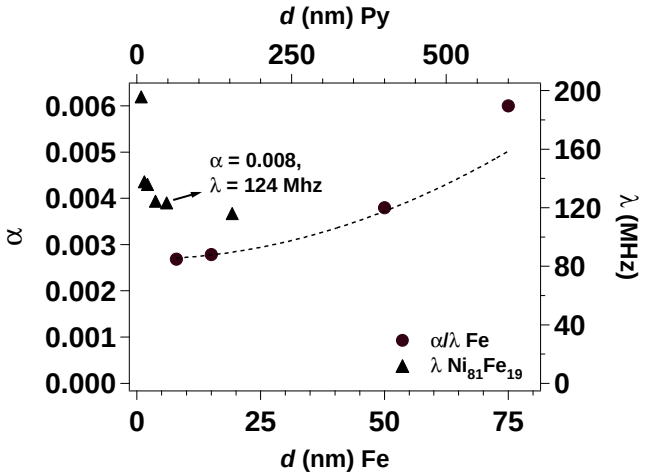

FIG. 3: Extracted damping constant α (left) and relaxation rate λ for epitaxial Fe films. The dashed line shows a calculated contribution of eddy currents to λ (Eq. 1). λ for $Ni_{81}Fe_{19}$ is plotted for comparison. See text for details.

as

$$\Delta\omega_{pp} = (2/\sqrt{3})\eta, \qquad (2)$$

[2]where $\eta = 1/\tau$, giving the decay time as $\exp -\eta t$ in a time-domain experiment,[3] and where $\eta_G = 2\pi\lambda$ in the absence of extrinsic relaxation. λ can be estimated in the intrinsic limit as $\lambda = (\sqrt{3}/2)\gamma\Delta H_{pp}$. We approximate extrinsic and intrinsic relaxation rates as $\eta \simeq \eta_0 + \eta_G$ with $\eta_0 = \sqrt{3}\gamma\Delta H_0$ measured in the absence of α.

Figure 4 shows a plot of the peak-to-peak swept-f FMR linewidths versus frequency for Fe (8 and 50 nm) and $Ni_{81}Fe_{19}$ (48 nm) films. It can be seen that the $Ni_{81}Fe_{19}$ films follow the intrinsic limit quite well, with $\Delta\omega_{pp}/2\pi = 129{\cdot}(2/\sqrt{3}) = 149$ Mhz (theoretical) approximated to 16 Ghz. However, the inhomogeneous term is appreciable in 8 nm Fe; $\Delta H_0 = 6 \pm 2$ Oe translates to $\eta_0 = 191 \pm 60$ Mhz and $\Delta\omega^0_{pp}/2\pi = (191$ Mhz$/2\pi) \cdot (2/\sqrt{3}) = 35 \pm 10$ Mhz, comparable to the observed $\Delta\omega_{pp}/2\pi - 2\lambda/\sqrt{3} \simeq 50 \pm 5$ Mhz.

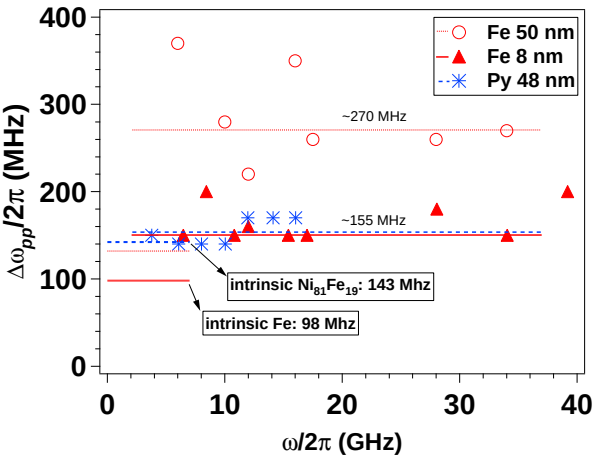

FIG. 4: Swept-frequency FMR linewidths $\Delta\omega_{pp}/2\pi$ for 8 nm and 50 nm epitaxial Fe; 48 nm (asterix) $Ni_{81}Fe_{19}$ is shown for comparison. Values of relaxation rate $\Delta\omega_{pp}/2\pi$ from Gilbert damping only are indicated.

IV. DISCUSSION

The observed low extrinsic relaxation rates are a plausible result of the excellent crystalline quality in the ultrathin epitaxial sputtered Fe films. Inhomogeneous broadening is more typically measured on the order of $\Delta H_0 =$ 50 Oe,[14] compared with the best of $\Delta H_0 = 6$ Oe seen here. X-ray diffraction rocking curves of the (200) peak on our films show full-width-half-maxima (FWHM) as low as 0.6°; more standard values for seeded epitaxy in sputtering for this system are 1.1°.[15] Moreover, easy-axis (<100>) coercivities H_c, measured by VSM, are 2.1 Oe compared with 3.7 Oe in Ref. [7] in thinner films (50 nm vs. 320 nm for MBE). The inhomogeneous linewidth is the lowest we are aware of in Fe films.

Finally we comment on applications. Favorable epitaxial structures in sputtered Fe/MgO/Fe junctions have resulted in very high tunneling magnetoresistance;[16] our results indicate that low α and high $\Delta R/R$ may coexist. Additionally, the low 35 Ghz frequency linewidths seen in our epitaxial Fe films could translate directly to high half-power Q in a frequency domain device. One example is a tunable bandstop filter based on FMR. We see $\omega/\Delta\omega_{1/2} = 140$ in our films, roughly an order of magnitude higher than that realized to date in Fe device structures.[17]

V. ACKNOWLEDGEMENTS

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